Journal Club for Condensed Matter Physics
https://www.condmatjclub.org
DOI:10.36471/JCCM_June_2025_03

Time-reversal symmetry breaking in superconductors detected by superconducting diode effect

1. **High-temperature field-free superconducting diode effect in high-T_c cuprates**
   Authors: Shichao Qi, Jun Ge, Chengcheng Ji, Yiwen Ai, Gaoxing Ma, Ziqiao Wang, Zihan Cui, Yi Liu, Ziqiang Wang and Jian Wang
   Nature Communications 16, 531 (2025).

2. **Superconducting diode effect and interference patterns in kagome CsV_3Sb_5**
   Authors: Tian Le, Zhiming Pan, Zhuokai Xu, Jinjin Liu, Jialu Wang, Zhefeng Lou, Xiaohui Yang, Zhiwei Wang, Yugui Yao, Congjun Wu and Xiao Lin
   Nature 630, 64 (2024).

Recommended with a Commentary by Youichi Yanase, Department of Physics, Kyoto University, Japan

In superconductors, electric resistance becomes zero, but it is not possible to pass an infinitely large electric current. The maximum current that can be passed while maintaining zero resistance is called the critical current, and in principle, it can depend on direction. If the critical current in one direction is not equivalent to the critical current in the opposite direction, passing a current whose magnitude is between the two critical currents will result in zero resistance in one direction and finite resistance in the opposite direction. This phenomenon is called the superconducting diode effect (SDE). Although there has been a long history of research on this phenomenon, it has recently become the subject of extensive research with expectations that it may be an intrinsic phenomenon of superconductors. The development of artificially controlled superconductors has also played an important role in revitalizing research on the SDE. Extensive research conducted over the past few years has demonstrated the SDE in various platforms.

Various mechanisms for the SDE have been proposed and demonstrated. They can be broadly classified into intrinsic mechanisms and extrinsic mechanisms. The former originates from the intrinsic properties of the superconducting phase such as the momentum of Cooper pairs that can be finite in the Fulde-Ferrell-Larkin-Ovchinnikov state, helical superconducting state, anapole superconducting state, and so on. The latter arises from sample edge asymmetries, for instance. The border between the two is unspecific, and identifying the mechanism behind the observed SDE is often a challenging task. On the other hand, there is a certain consensus regarding the symmetry requirements. The SDE is considered to require the breaking of spatial inversion symmetry and time-reversal symmetry.

For example, when a magnetic field is applied to a polar system, the structural symmetry breaks inversion symmetry, and the external magnetic field breaks time-reversal symmetry. If the polarization $\vec{P}$ and the magnetic field $\vec{H}$ are perpendicular to each other, the outer product $\vec{P} \times \vec{H}$ becomes finite. This quantity has the same symmetry as the charge current, suggesting that non-reciprocal transport occurs in that direction. The SDE is an extreme example of non-reciprocal transport, and it indeed occurs in this case. The setup in which the SDE occurs is not limited to this case; it can also occur in materials with non-polar chiral crystal structures, for instance.

If the above symmetry requirement is correct, it may be possible to probe the symmetry of quantum phases using the SDE. If the SDE is observed in superconductors, it is concluded that both inversion symmetry and time-reversal symmetry are broken. However, spatial inversion symmetry is generally broken due to an extrinsic origin such as the sample edge asymmetry, and this effect is particularly important for the extrinsic SDE. Therefore, careful attention is required to detect intrinsic breaking of spatial inversion symmetry. On the other hand, it is rare for time-reversal symmetry to be broken for such extrinsic reasons. Therefore, the use of SDE for detecting time-reversal symmetry broken superconductors is promising.

The origins of time-reversal symmetry breaking in the superconducting state can be broadly classified into the following three categories.

(1) External magnetic field
(2) Electronic order that breaks time-reversal symmetry already in the normal state above T_c.
(3) Spontaneously time-reversal-symmetry-breaking superconducting order parameter

In most of previous studies, the SDE has been observed in case (1). The other two cases do not require an external magnetic field, making the field-free SDE possible. Exploring the field-free SDE is a critical issue from an application perspective. In this context, a common approach is to search for superconductivity coexisting with electronic order that breaks time-reversal symmetry, such as ferromagnetism and altermagnetism. Meanwhile, is it possible to identify the symmetry and order parameters of quantum phases using the field-free SDE?

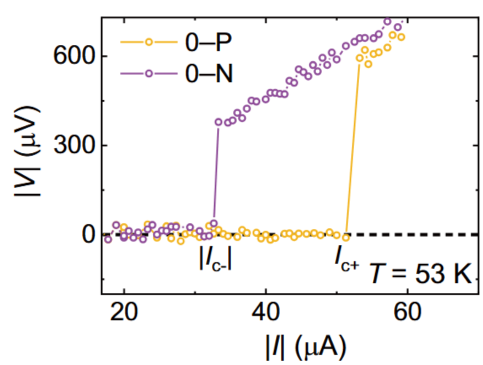

Fig.1: V-I curves observed in a high-temperature cuprate superconductor. Critical current is different between the positive (0-P) and negative (0-N) directions at zero magnetic field. This demonstrates a field-free SDE. Figure is adopted from the recommended paper.

The recommended paper 1 reports the field-free SDE in copper oxide high-temperature superconductors (Fig. 1). The diode efficiency, which indicates the quality of the SDE, reaches a maximum of 22%, which, though not a record, is an extremely high value. This efficiency observed at high temperature T=53 K signifies the realization of a "user-friendly" SDE. The cause of the breaking of time-reversal symmetry is likely to be case (2). The clarification of the anomalous metallic phase in high-temperature cuprate superconductors remains a major challenge in condensed matter physics. The observation of the field-free SDE suggests that time-reversal symmetry is broken above the superconducting transition temperature, thereby contributing to the long-standing debate. Loop current order, proposed for the anomalous metallic phase, breaks time-reversal symmetry, and analysis of the SDE has been conducted based on the related theory. Note that twisted trilayer graphene is another platform of the field-free SDE in case (2), where valley polarization is thought to simultaneously break time-reversal symmetry and spatial inversion symmetry.

The recommended paper 2 reports the field-free SDE in the kagome superconductor CsV_3Sb_5. While the SDE in copper oxide high-temperature superconductors is relatively stable under thermal cycling, the SDE in the kagome superconductor is extremely sensitive to thermal cycling. Case (3), which assumes chiral superconductivity that spontaneously breaks time-reversal symmetry, can explain this difference. In chiral superconductors, chiral domains with opposite orbital magnetization may emerge, and it is natural to assume that the domain structures change under thermal cycling. Experimental results showing significant differences in the SDE during thermal cycles up to temperatures slightly above the superconducting transition temperature support this interpretation. Additionally, the recommended paper 2 reports oscillations in the critical current in weak magnetic fields. Behaviors similar to Little-Parks oscillations suggest that chiral domains are regularly structured, although the details of the domain structures remain unclear. The asymmetry of the oscillations is closely related to the SDE, supporting the claim that topological edge states appearing at chiral domain walls are the origin of the SDE. This interpretation, edge states characteristics of topological superconductors result in the field-free SDE, is highly intriguing, but further verification is desired. In kagome superconductors, chiral CDW order breaking time-reversal symmetry above the superconducting transition temperature has been reported. The field trainability reported recently by Peking university group, including authors of the recommended paper 1, demonstrates that the time-reversal symmetry breaking due to CDW order also influences the SDE.

Experiments using SDE to verify the broken time-reversal symmetry in superconductors are potentially applicable to a wide range of materials, and further research is expected in the future. However, the goal is still far off. There is much debate about the symmetry breaking in high-temperature cuprate superconductors, and experimental results ruling out chiral superconductivity in kagome superconductors have also been reported. The mechanisms by which time-reversal symmetry breaking in superconductors enables the SDE are diverse, making understanding them challenging. Furthermore, an experiment has reported the SDE in superconductors where time-reversal symmetry is not expected to be broken. This observation is open to further interpretation. Could it be due to hidden symmetry breaking? or a nonequilibrium phenomenon? Does it call for further study of the SDE with an unknown origin?

If the use of SDE in condensed matter physics is established, research on superconductors will advance significantly. Unconventional superconductors with symmetry breaking are attracting considerable attention, and the development of experimental techniques to determine their symmetry is a central issue. In addition, unconventional superconductors are strong candidates for topological superconductors, making research toward their verification important as well.